

GROUND MOTION DIRECTIONALITY IN HETEROGENOUS SITE

M.R. GHAYAMGHAMIAN¹

SUMMARY

The directionality of strong ground motion was investigated using downhole array recordings at Sendai City in Japan. The principal direction of motion was calculated for each level of the borehole. Different directionality of motion was observed at different loOcations and in different levels of the borehole at the sites. The cross-coupling of motion in different orthogonal directions due to geological irregularities and wave propagation in heterogeneous wave field is used to explain the observed phenomena at the sites. The analytical model is introduced to account for motion coupling in two horizontal directions as well as three orthogonal directions based on wave propagation theory. The cross-coupling coefficients are introduced to quantify the observed geological irregularities and their effects on strong ground motion. Finally, the outcome provides a field evidence of ground motion directionality caused by motion cross-coupling at the sites.

INTRODUCTION

The characteristics of earthquake ground motion can be significantly influenced by local site conditions. The damage distribution of recent earthquakes added more examples to illustrate this fact and manifested the local site effects on strong ground motion characteristics. An earthquake motion can be amplified at certain frequencies depending on the physical properties of the soil. In addition, complex effects of wave propagation in the surface layers, that actually include anisotropy, heterogeneity, irregular boundaries etc, are manifested in particular in different types of wave conversions and/or coupling between motions in the orthogonal axes. The effects of cross-coupling among motions in different directions may remarkably change the characteristics of strong ground motion at the site [1,2,3]. Given the possibility of the large damage that can be followed, it is of practical importance to accurately evaluate the site response, especially for choosing the location and designing of the critical facilities. Accordingly, a comprehensive study on this subject is required because of the possible influence of this phenomenon on the strong ground motions and its directional dependence. Furthermore, knowledge of directional dependence of strong motions may aid in predicting the dominant direction of damage at the site.

¹ Assistant Professor, Engineering Seismology Dept., International Institute of Earthquake Engineering and Seismology (IIEES), P.O. Box 19395-3913, Tehran, Iran.

In general, ground motion directionality can be produce by two major factors, namely, source and irregular underground structure effects. The directionality due to source effect is mostly observed in near-source ground motion, where the dimension of the fault is comparable to the site-to-fault distance. In the latter case, the directionality in strong ground motion induced by the interference of ground motions in different directions due to wave propagation in the irregular underground structure. Ghayamghamian and Motosaka (2003) showed that the ground motion directionality could be also induced due to the wave propagation in surface layers, when the soil material is complex (anisotropy, heterogeneity, etc.) [4]. In fact, they believed that ground motion directionality due to any of the above mentioned reasons will result in cross-coupling effects among different orthogonal directions.

In this paper, the downhole array recordings at Sendai City in Japan were analyzed. The principal direction of motion was calculated for each level of the borehole. Different directionality of motion was observed among different levels of the borehole at the sites. A good correlation between observed directionality and surface as well as sub-surface geology of the sites was used to explain the observed phenomena at the sites. The coupling of motion in different orthogonal directions is introduced as a secondary effect of the observed phenomena at the site. The analytical model is developed to account for motion coupling in two and three directions using wave propagation theory. The cross-coupling coefficients were introduced to quantify the geological irregularities effect on strong ground motion and site amplification characteristics.

SENDAI DOWNHOLE ARRAY AND EARTHQUAKE DATA

The Sendai region is located about 300 km north of Tokyo in Japan (Fig. 1). Most of the Sendai region is in the city of Sendai, whose population is about one millions. The thickness of quaternary layers including alluvium in the region is nearly 0 m from the west of the Rifu-Nagamachi fault, it becomes 20 to 40 m abruptly at the fault vicinity and increases to 60-80 m to the east. In the north, tertiary or pre-tertiary rock is outcropping. It should be noted that the thickness of quaternary layers are very small, except at Rifu-Nagamachi fault as shown by contours in Figure 1.



Fig.1 Map of Japan and location of vertical array sites.

The Sendai array network established as a project by Building Research Institute (BRI), Ministry of Construction, and the Association for Promoting Building Research (APBR) since 1987 [5,6]. The objective of this array network is to evaluate local site effects and to develop a rational seismic design method. The array network is composed of 11 stations with spacing of approximately 3 to 5 km on the E-W and N-S lines passing through the center of Sendai City. At each station, three observation points are arranged vertically at surface (-1 or -2 m), level of -20 to -30 m and at a depth of about -50 to -80 m. The deeper stations at each site are located on the engineering bedrock, where the shear wave velocity is in the range of 700-800 m/s. Data of 3 vertical array sites is used in this analysis. Descriptions of soil parameters for the sites at which the geotechnical and geophysical field explorations have been carried out together with the location of borehole accelerometers are given in APBR reports [5,6].

The main shock of Miagiken-Nanbu earthquake (M=5.0) was used for the analysis here. The after shock area was 3 km by 3 km with the hypocenter located on the plane of Rifu-nagamachi fault. Figure 2 shows an example of recorded surface accelerations for the NS and EW components at the surface.



Time (sec)

Fig.2 An example of surface accelerograms in the NS direction at the sites.

DIRECTIONALITY OF STRONG GROUND MOTIONS

Figure 3 shows the acceleration orbit of strong ground motions in horizontal plane for different levels of the boreholes at the sites. Furthermore, the principal directions of the recorded ground motions are calculated using the method developed by Penzine [7]. Based on this technique, the variance-covariance matrix as given in Equation (1) is calculated from the horizontal ground acceleration data at a site.

$$E = \sum_{i=1}^{n} \begin{bmatrix} x_i x_i & x_i y_i \\ y_i x_i & y_i y_i \end{bmatrix} dt$$
(1)

where x_i and y_i are the acceleration data at EW and NS directions, respectively, n is the number of data, and dt is the sample interval of the record. The directions of principal axes are the calculated eigen vectors from the variance-covariance matrix as given by Equation (2):



Fig.3 Acceleration orbits and calculated principal strong direction of motion.

$Ea = \lambda^2 a$

(2)

where λ_2 , λ_2 are the eigen values and $\lambda_2 a_1$, $\lambda_2 a_2$ are eigen vectors in strong and weak directions, respectively.

The red straight lines in Figure 3 shows the calculated strong principal direction for different levels at the sites. As shown in this figure, the principal direction of the motion is changing at the sites. It is also interesting to note that how the principal direction of the motion is changing as the input motion propagating from the engineering bedrock to the surface at the sites. In this figure, Tama, Trga and Tsut sites do not show clear directionality in their horizontal orbits. However, the other sites show apparent directionality in their horizontal orbits. Furthermore, Trma site clearly shows the torsional motion in its horizontal orbit. To explain the appearances of such a phenomena at the sites, the cross-section of Sendai region along the line c-c' is shown in Figure 6. As can be seen in this figure, the sites located near the geological irregularities clearly show the directionality in their horizontal orbits. However, the sites located on the irregular surface or sub-surface geology do not show any directionality in their orbits. For instance, both Tama and Orid sites are located on the same geological unit (soft rock), however, Orid site show directionality in its horizontal orbits but Tama site does not. Looking at cross-section shown in Figure 4, it can be seen that Orid site are situated near to the topography but Tama site situated in flat surface. In addition, the sites located near to the sub-surface geological irregularities such as Miya, Okin, Shir and Naga sites clearly show the directionality in their orbits. Therefore, the directionality of strong ground motion at Sendai region may be attributed to the geological irregularities at the Sendai region.



Fig.3 Continued.

However, it is interesting to note that the directionality of motion not only changes based on the positions of the sites with respect to the geological irregularities, but also it is changing in different levels at the same site. This can be attributed to the strong heterogeneity between different sediments at the sites [4]. Therefore, both geological irregularities and sediment heterogeneity can affect the directionality of the motions at the site.

CROSS-COUPLING EFFECTS

The ground motion directionality is actually produced due to wave propagation in complex wave field including irregular boundaries, heterogeneity, anisotropy, etc. These factors cause the coupling between strong ground motions in different orthogonal directions. In other words, propagating of the motion in such a media cause the coupling of motion in different directions. Therefore, When cross-coupling happen, the motion in one direction can produces the motion in other directions, and then the motion in different directions are dependent to each other and cannot be separately considered. Ghayamghamian and Motosaka (2003) has been developed the wave equation to account for cross-coupling between different orthogonal directions. They expand the 1D wave propagation in its matrix form to account for cross-coupling in three orthogonal directions (x, y for horizontal directions and z for vertical direction) can be given as [8]:



Acceleration in NS Direction (cm/s²)

Fig.3 Continued.

$$\begin{bmatrix} G_{xx} & G_{xy} & G_{xz} \\ G_{yx} & G_{yy} & G_{yz} \\ G_{zx} & G_{zy} & G_{zz} \end{bmatrix} \frac{\partial^2}{\partial z^2} \begin{cases} u_x \\ u_y \\ u_z \end{cases} = \begin{bmatrix} \rho & 0 & 0 \\ 0 & \rho & 0 \\ 0 & 0 & \rho \end{bmatrix} \frac{\partial^2}{\partial t^2} \begin{cases} u_x \\ u_y \\ u_z \end{cases}$$
(3)

where G_{xx} , G_{yy} and G_{zz} are shear modulus in x, y and z directions, respectively, the off-diagonal terms are coupled shear modulus between different directions, ρ =mass density, u_x =displacment in x direction, u_y =displacement in y direction, and u_z =displacement in z direction (for simplicity, the argument is omitted here, e.g. $u_x(z,t)=u_x$). Introducing the parameters $\alpha=G_{xy}/G_{xx}=G_{yx}/G_{xx}$ $\beta=G_{xz}/G_{xx}=G_{zy}/G_{xx}$, $\gamma=G_{yz}/G_{xx}=G_{yz}/G_{xx}$. Equation (1) can be written as:

$$\rho v_x^2 \begin{bmatrix} 1 & -\alpha & \beta \\ -\alpha & \xi_1^2 & \gamma \\ \beta & \gamma & \xi_2^2 \end{bmatrix} \frac{\partial^2}{\partial z^2} \begin{cases} u_x \\ u_y \\ u_z \end{cases} = \begin{bmatrix} \rho & 0 & 0 \\ 0 & \rho & 0 \\ 0 & 0 & \rho \end{bmatrix} \frac{\partial^2}{\partial t^2} \begin{cases} u_x \\ u_y \\ u_z \end{cases}$$
(4)

In Equation (4), parameters α , β and γ are accounted for cross-coupling among different orthogonal directions (hereafter referred to as coupling coefficients). Likewise, parameter ξ_1^2 and ξ_2^2 stand for the difference between soil properties in different orthogonal directions.

There are some cases that the coupling of motion happens only between horizontal motions in horizontal plane (*i.e.* the motions in EW and NS directions are only coupled) and there is no coupling between horizontal and vertical directions. In that case, the above equation can be simplified as:

$$\begin{bmatrix} G_{xx} & G_{xy} \\ G_{yx} & G_{yy} \end{bmatrix} \frac{\partial^2}{\partial z^2} \begin{cases} u_x \\ u_y \end{cases} = \begin{bmatrix} \rho & 0 \\ 0 & \rho \end{bmatrix} \frac{\partial^2}{\partial t^2} \begin{cases} u_x \\ u_y \end{cases}$$
(5)



Fig.4 Typical geological profile given along the line indicated by cc' in Figure 1.

where $G_{xx} = \rho v_x^2$ and $G_{yy} = \rho v_y^2$ denote shear modulus in x and y directions, respectively, $G_{xy} = G_{yx}$ = coupled shear modulus, ρ =mass density, v_x = shear wave velocity in x, v_y = shear wave velocity in y direction. u_x =displacement in x direction and u_y =displacement in y direction. Again, by introducing parameters $\alpha = G_{xy}(G_{yx})/G_{xx}$ and $\xi_1^2 = G_{yy}/G_{xx}$, Equation (1) can be written as:

$$\rho v_x^2 \begin{bmatrix} 1 & -\alpha \\ -\alpha & \xi_1^2 \end{bmatrix} \frac{\partial^2}{\partial z^2} \begin{cases} u_x \\ u_y \end{cases} = \begin{bmatrix} \rho & 0 \\ 0 & \rho \end{bmatrix} \frac{\partial^2}{\partial t^2} \begin{cases} u_x \\ u_y \end{cases}$$
(6)

Parameter α is accounted for coupling between the horizontal motions. Likewise, parameter ξ_1^2 defines the difference between soil properties in two horizontal directions.

Equations (4) and (6) can be solved using wave propagation theory [4]. By solving the above equations, the transfer function and motion directionality for different soil level can be investigated. In practice, the cross-coupling coefficients can be back-calculated by optimizing the theoretical amplification function with actual ones. These parameters can be used to identify the unknown sub-surface geological irregularities in seismic hazard mitigations and seismic microzontaion.

DISCUSSION AND CONCLUSIONS

In this paper, the strong motion directionality was investigated by principal axes analysis using downhole array data at Sendai City in Japan. Data of Miagiken-Nanbu earthquake were analyzed in this study. The strong directionality in recorded ground motion was identified at the sites by visual inspection of changes in calculated principal direction axes of motion in different sites and levels. The good correlation between the directionality of motion and geological irregularities at the sites is used to verify the reasons of observed phenomena as a surface and sub-surface geological irregularities. In addition, the principal direction of motion varied in different levels at the site that attributed to the heterogeneity of the surface

soil layers at the site. The wave propagating in complex wave field was analytically investigated. The wave equation was developed for both 2D and 3D coupling in complex media by introducing coupling coefficients in the model. Practically, the coupling coefficients can be back-calculated using soil amplification function and strong ground motion. These coefficients can be utilized in seismic hazard mitigations as the factors to identify the unknown sub-surface geological irregularities in large area for seismic microzonation proposes.

Since the source of earthquake was very near to the sites, some researchers believed that the observed directionality could be attributed to the near-source effect. Among them, Kamiyama et al. (2000) made an effort to simulate the motions at the surface by considering the source parameters obtained from the inversion analysis of low frequency motion [9]. They draw the acceleration orbits of simulated motions and compared them with the actual ones, some discrepancies in the direction of motion orbits at surface between the actual and simulated ones is identified, especially for the sites located at basin. This may confirm the large contribution of geological irregularities to strong motion directionality in Sendai region. The observed strong motion directionality in different levels of the downhole at the sites is attributed to

the surface layer heterogeneity at the sites (*e.x.* Trma site). Previously, two factors are used to explain ground motion directionality at the site. The outcome of this paper also adds one more possibility to cause ground motion directionality as surface layer heterogeneity.

ACKNOWLEDGMENTS

The author would like to acknowledge the generosity of Building Research Institute (BRI), Ministry of Construction, and the Association for Promoting Building Research (APBR) in sponsoring further investigation of earthquake engineering. Without the data provided through their support, this study would not have been possible.

REFERENCES

- 1. Bard P.Y. "Effects of surface geology on ground motion: recent results and remaining issues." In Proc. of the 10th European Conf. on Earthquake Engineering, Vienna, Austria, 1994, Vol. 1.
- 2. Tumarkin A.G. "Site response analysis in 3D." In: Proc. of the Int. Symp. on the Effects of Surface Geology on Seismic Motion" Yokohama, Japan, 1998, Vol. 2:365-370.
- 3. Paolucci R. "Numerical evaluation of the effect of cross-coupling of different components of ground motion in site response analyses.", Bull. Seism. Soc. Am. 1999; 89(4):877-887.
- Ghayamghamian M. R. and Motosaka M. "The effects of torsion and motion coupling in site response estimation.", Journal of Earthquake Engineering and Structural Dynamics, Vol. 32, No. 5, pp. 691-709.
- 5. Association for Promoting Building Research. Reports of survey and study on dense strong motion earthquake seismometer array observation project, 1987-1990 (in Japanese).
- 6. Association for Promoting Building Research. Report on Sendai strong motion array network, 1999 (in Japanese).
- 7. Penzine J, Watabe M. "Charachteristics of 3-Dimentional earthquake ground motions." Earthquake Engineering and Structural Dynamic, 1975 (3), pp. 365-373.
- 8. Ghayamghamian M. R. and Motosaka M. "The effects of ground motion cross-coupling on site amplification characteristics", Journal of Soil dynamics and earthquake engineering, (submitted).
- 9. Kamiyama M, Asada A, Matsukawa T, Shoji Y. "On-line Small-Titan strong motion system", Tohoku Journal of natural disaster science; 2000 (36), pp. 25-30 (in Japanese).